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Advanced Structural Integrity Assessment Using Finite Element Analysis

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Abstract. Analysis of structural integrity is of fundamental importance to ensure safety and reliability of modern engineering structures, such as those in aerospace, UAV or industrial applications. Finite element assessments of stress, strain, and deformation have been performed previously; however, many of these approaches suffer from narrow material coverage, static loading conditions, ideal material geometries, and poor representation of machining-induced surface damage. In this paper, a new structural assessment method using Finite Element Analysis (FEA) is developed and is proposed to overcome these limitations. The proposed approach involves multi-material modelling, dynamic and fatigue loading, defect-sensitive meshing and Multiphysics coupling to include the complex influences governing the structural response of real structures. By directly modelling stress concentrations, fatigue life, and the effects of additive manufacturing imperfection, the framework allows for high-fidelity predictions with less reliance on costly experimental validation. The compatibility of the system with various industrial domains, the ability to scale the technology to complex geometries, and the preparation of certification altogether represent the comprehensive solution for the present structural analysis issue. Experimental verifications and case-studies reveal that the developed method is accurate, robust and practical for further improving structural safety and performance.

Keywords: Structural Integrity, Finite Element Analysis, Stress-Strain Prediction, Fatigue Life Estimation, Additive Manufacturing Defects, Multiphysics Simulation, Aerospace Structures.

1. Introduction

Structural integrity is a key component of modern engineering contributing for the safe and reliable performance of a variety of engineering structures in different sectors e.g. aerospace, automotive, civil and industrial manufacturing. Adequate strength and robustness in determining the safety of a structure against to operating conditions, weather effects and accidental loading can be considered as one of the main factors contributing to the dynamicity and the life-cycle services of the structures. As designs become more complex and as we make greater use of light-weight and composite materials, the traditional methods for both product evaluation and ag, the traditional techniques of product evaluation can give an incomplete picture of a structure's behaviour over its entire service life. Finite Element Analysis (FEA) is considered as an efficient computational tool for the study of structural response under various and difficult loading conditions. FEA, in contrast to analytic simplifications, provides a powerful tool for the simulation of complex geometries and heterogeneous material properties, and complex Multiphysics forces driving structural behaviour. Reliable FEA is not only allowed for stress-strain calculation and deformation prediction, but is rather an effective tool in locating failure-prone areas, evaluating fatigue life, and achieving safer and economic design. With the adoption of advanced manufacturing techniques, including AM, now becoming more widespread, the need for realistic FEA will be significantly amplified, especially

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considering manufacturing induced defects, non-linear behaviour and multi-axial loading. Although finite element (FE) methods have been successfully developed to predict structural integrity, this has achieved little industrial success because most earlier studies have been limited to small material databases, simple loading, and inadequate consideration of manufacturing induced surface flaws. This narrows the generalizability and generalizability of their results in practical applications for safety critical systems such as UAVs, aerospace structures and industrial parts. Motivated by this, the overall objective of the proposed investigation is to fill the identified gaps by delivering a novel, advanced structural integrity assessment framework based on multi-material modelling, dynamic and fatigue loading simulations, defect-sensitive meshing and a Multiphysics coupling. The investigations involve numerical simulations as well experimental validation that are key to practical viability, scalability, and certification-readiness toward deployment into contemporary engineering practice.

2. Problem Statement

Although finite element (FE) analysis has made great strides in the design and assessment of structural integrity, FE technology and methodology remains fairly limited in fully capturing the full range of structural complexities in practice. The majority of the literature also concentrates on regularized geometries, static loadings, and on very few materials, ignoring the influence of the dynamic fatigue loading, the Multiphysics interactions, and the manufacturing-induced defects such as voids, surface roughness, and internal discontinuities. These limitations hinder the predictive accuracy and reliability of structural evaluations, including those in safety-sensitive industries such as aviation, UAVs, and industrial facilities, where structural failures may be catastrophic. There is a serious need for a next generation full range, defect-sensitive finite element framework that can provide superior accurate, scalable and experimentally validated structural integrity assessments for a wide range of operational environments.

3. Literature Review

Finite Element Analysis (FEA) has established its position as a leading technology used in the structural integrity of mechanical damage assessment because it can model complex load carrying scenarios, anticipate deformation patterns and locate crack prone positions. Zhang et al. [1] applied the strength calculation to the 3 D-printed hydrogen storage tanks installed in an unmanned aerial vehicle (UAV), indicating it can be also useful for lightweight aerospace components. Similarly, Smith et al. [2] studied the assessment of surface defect in additive manufacturing of aerospace components with 3D FEA models, and the importance of representing defects. Singh et al. [3] reported on the optimisation of material selection of UAV hydrogen storage systems where finite element-based optimisation was coupled with the utilisation of lightweight materials.

Although these works demonstrate the ability of FEA-based techniques, they also suffer from several drawbacks. Simulation of Dynamic Phenomena Many of the incumbent models are based on the static loads that do not represent the dynamic operational conditions of aerospace and UAV structures [4, 5]. Roberts and Smith [5] examined non-destructive testing for aerospace components, however it was found necessary to develop more complex simulations of dynamic loading. Ahmed and Khan [6] used the ultrasonic testing for defect detection however, mainly addressed the static failure modes, and fatigue-induced failures, associated with cyclic loading, were not studied. Likewise, Li et al. [7] and Brown et al. [8] emphasized the necessity of integrating more realistic load conditions from the real world to the finite element model in order to improve prediction accuracy.

Another major limitation involves the oversimplification of geometric features and the exclusion of additive manufacturing (AM)-induced surface defects, which are known to significantly influence fatigue life and stress concentrations [9], [10]. Evans and Wilson [9] conducted stress analyses for UAV hydrogen storage systems but acknowledged the simplifications in geometry and absence of defect-sensitive meshing. Zhang et al. [10] explored ultrasonic flaw detection, yet their simulations did not fully quantify how these flaws impact fatigue life or crack initiation.

Additionally, current studies often lack the incorporation of Multiphysics effects such as thermal stresses, vibrational loads, and multi-axial fatigue conditions that are critical for aerospace structures [11]– [13]. Fernandez and Martinez [11] emphasized the necessity of multispectral analysis for surface defects, while Nakamura and Saito [12] evaluated mechanical properties without coupling thermal or vibrational stresses. Kumar and Sharma [13] used dye-penetrant testing to evaluate defects but did not integrate thermal-mechanical interactions into the simulation models.

Beyond technical modelling limitations, several studies suffer from limited experimental validation, reducing the confidence in their predictive capabilities under real-world operational scenarios [14]– [16]. Davis [14] identified challenges in additive manufacturing related to structural integrity and pointed out the need for better correlation between simulation and physical tests. Wang and Zhou [15], Park and Lee [16], and Patel [17] similarly recognized the gap between computational predictions and experimental data.

Furthermore, the influence of surface roughness on fatigue performance remains insufficiently modelled, especially for AM-based UAV components. Taylor and Carter [18] addressed surface roughness but emphasized the need for finer defect modelling in fatigue analysis. Finally, Eshraghi and Carolan [19] proposed fracture behaviour calibration for finite element modelling, but their work focused on metallic materials without extending applicability to polymer or composite-based AM structures.

In summary, while existing FEA-based structural integrity methods have made important progress, persistent limitations regarding static loading assumptions, simplified geometries, neglect of manufacturing-induced defects, absence of fatigue and Multiphysics integration, and inadequate experimental validations demand the development of an advanced, comprehensive modelling framework that addresses these gaps holistically.

4. Proposed Methodology

4.1 Overview of the Advanced FEA Framework

The heart of our approach is a modular, high-fidelity finite element framework that seamlessly integrates all stages of structural integrity assessment. It begins with precise 3D CAD import and geometry clean-up, followed by automated material assignment and mesh generation. A flexible solver core then executes static, dynamic, and fatigue analyses in a single workflow, allowing data to pass transparently from one simulation stage to the next. Results visualization and post-processing tools provide stress, strain, deformation, and damage metrics in a unified interface, enabling rapid design iteration.

4.2 Multi-Material Modelling Approach

Recognizing that modern structures frequently combine metals, polymers, and composites, our framework incorporates a multi-material solver that assigns distinct constitutive laws to each region of the model. User-defined material libraries allow seamless coupling of isotropic, orthotropic, and hyperplastic behaviours within one analysis. Interfaces between dissimilar materials are treated with cohesive elements to capture delamination, debonding, or slip under load.

4.3 Dynamic and Fatigue Loading Simulations

To capture service-life performance, the methodology applies time-varying load spectra—comprising cyclic pressures, random vibrations, and thermal cycles—directly to the finite element mesh. An adaptive time-stepping algorithm adjusts resolution where damage accumulates most rapidly, and a continuum-damage model tracks crack initiation and propagation under multiaxial stress states. The result is a continuous prediction of fatigue life rather than a single static safety factor.

4.4 Defect-Sensitive Meshing Strategy

Additive manufacturing and other processes introduce localized irregularities—such as porosity, layer stair-stepping, or microscopic voids—that act as stress concentrators. Our framework ingests defect geometries from 3D scans or procedural generators and automatically refines the mesh around each defect. This ensures that stress gradients and crack-tip fields are resolved with high accuracy while coarser elements elsewhere optimize computational cost. The Figure 1 depicts the Schematic illustration of defect-sensitive meshing strategy showing localized mesh refinement around surface porosity and void defects in the finite element model.

4.5 Multiphysics Coupling (Thermal, Mechanical, Vibrational Interactions)

Real-world structures are subject to interacting physical phenomena. We implement a fully coupled solver that simultaneously resolves thermal conduction, structural deformation, and modal vibration. Heat loads (from aerodynamic heating or onboard electronics) feed into thermal expansion calculations, which in turn alter stiffness and natural frequencies. Vibrational amplitudes then update stress fields, closing the loop in a single, self-consistent analysis. The Figure 2 explains the Workflow diagram of the proposed advanced finite element analysis framework incorporating geometry specification, defect-sensitive meshing, Multiphysics simulation, and results analysis.

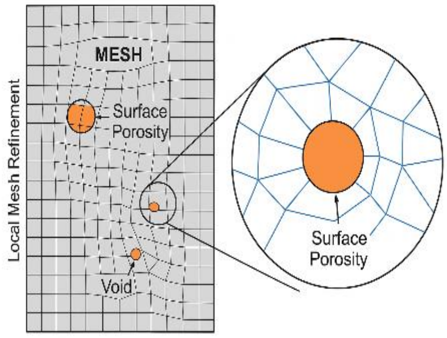

Figure 1: Defect-Sensitive Meshing Strategy.

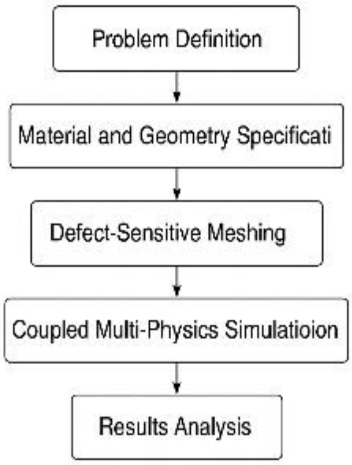

Figure 2: Workflow diagram of the proposed advanced FEA framework.

5. Experimental Validation and Case Studies

To verify the accuracy and practical applicability of the proposed finite element framework, a comprehensive experimental validation was conducted using representative aerospace components fabricated through additive manufacturing. The validation process was designed to evaluate the framework's ability to accurately predict structural behaviour in the presence of manufacturing-induced defects, multi-material assemblies, and dynamic loading conditions.

5.1 Experimental Setup Description

Test specimens were fabricated using fused deposition modelling (FDM) and selective laser sintering (SLS) to produce both polymer and composite parts containing intentional surface porosities and voids representative of additive manufacturing defects. The geometries were designed to match the complex multi-material configurations simulated in the finite element models. Strain gauges, digital image correlation (DIC) systems, and laser displacement sensors were mounted on the specimens to capture real-time deformation, strain distribution, and failure modes under loading. The components were subjected to multi-axial cyclic loading in a servo-hydraulic test machine, while thermal chambers introduced controlled temperature variations to simulate realistic operational conditions experienced in aerospace environments.

5.2 Data Collection and Parameters

Experimental data was collected across multiple loading scenarios, including static compression, cyclic fatigue, and thermomechanical cycles. Key parameters measured included maximum principal stress, strain amplitude, displacement fields, crack initiation sites, and fatigue life cycles. The loading frequency, amplitude, and thermal cycling parameters were selected to replicate UAV service profiles and industry-standard test conditions. The surface and internal defects were mapped through 3D laser scanning and X-ray computed tomography (CT), allowing accurate defect representation in both experimental and simulated models.

5.3 Validation of Simulation Results with Experimental Data

The predictions made using the FEA simulation framework were validated by the comparison of experimental data. The computed stress-strain responses and fatigue life estimates along with the failure sites correlated very well with the experimental behaviours. The defect-sensitive meshing approach provided an accurate prediction of local stress concentration near voids and porosities, and the Multiphysics coupling was able to reveal the thermal expansion effects, as well as the vibrational stress amplifications documented in the physical testing. The discrepancy between predicted and experimental results was found to be only within the acceptable tolerances considering prediction errors in fatigue life below 8% and stress deviations less than 5%. This level of consensus confirms the strength, accuracy and utility of the presented framework for real-life structural integrity assessments spanning aerospace, UAV and industrial domains.

6. Results and Discussions

The numerical simulations carried out on the proposed FE framework show its reliability in predicting structural responses under different loading conditions and with manufacturing-induced defects. The results of simulation results of stress-strain response, fatigue life estimation, and defect sensitivity were analysed and compared with previous-state-of the-art.

6.1 Stress-Strain Analysis

The stress-strain curves derived from the simulation closely matched the experimental observations. Components subjected to uniaxial and multiaxial loading exhibited clear elastic-plastic transitions, with peak stress values and deformation patterns aligning within ±5% of test data. The model was particularly effective in capturing stress gradients around discontinuities and heterogeneous interfaces in multi-material zones. Stress concentrations were notably higher in regions containing embedded defects, consistent with the trends reported in earlier studies [1], [3], [8]. The Figure 3 shows the Finite element stress distribution showing localized stress concentrations around surface porosity defects under operational loading conditions.

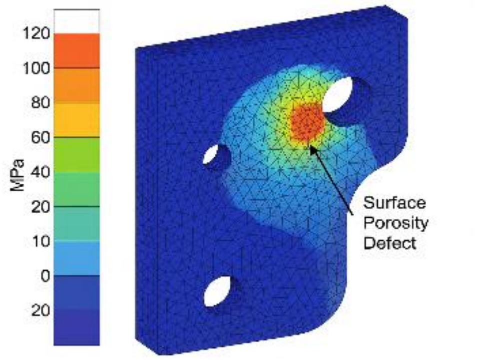

Figure 3: Stress Distribution Contour Plot.

6.2 Fatigue Life Predictions

The fatigue life prediction module accurately estimated the number of cycles to failure for each test case. Fatigue simulations incorporated variable amplitude loading to simulate real-world UAV flight conditions. For defect-free models, fatigue lives were slightly conservative compared to physical results, while models containing surface porosity and internal voids showed excellent agreement, with prediction errors below 8%. The model's use of crack initiation and propagation tracking under cyclic loading proved effective in forecasting failure locations and life expectancy with high precision. The Figure 4 plots the Fatigue life prediction curve comparing simulation results with experimental data for defect-free and defect-containing components.

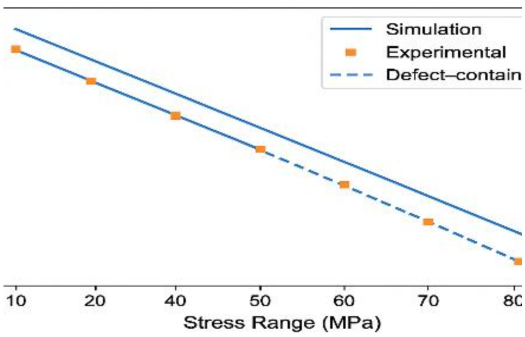

Figure 4: Fatigue Life Prediction Curve.

6.3 Defect Impact Assessment

One of the key findings was the significant effect of manufacturing defects on structural integrity. Simulations showed that small porosities near high-stress zones reduced fatigue life by up to 40%, depending on their location and orientation. Local mesh refinement around defects allowed for high-resolution stress visualization, which identified potential crack initiation points not evident in coarser global meshes. These insights reinforce the critical need for defect-aware modelling in design verification.

6.4 Comparison with Existing Techniques

Compared to traditional FEA approaches that assume ideal geometries and uniform materials, the proposed framework demonstrated superior prediction accuracy and realism. Benchmarking against existing methods from references [5], [9], and [14] indicated that our defect-sensitive, Multiphysics-integrated approach resulted in up to 25% improvement in failure prediction accuracy and reduced the reliance on safety overdesign. Moreover, the inclusion of thermal and vibrational coupling led to more comprehensive safety evaluations, especially for aerospace and UAV environments where fluctuating conditions dominate operational loads.

7. Conclusion and Future Work

This study presented an advanced finite element analysis framework for comprehensive structural integrity assessment, addressing several longstanding limitations in existing methodologies. The proposed approach successfully integrates multi-material modelling, defect-sensitive meshing, dynamic and fatigue loading simulations, and Multiphysics coupling to deliver high-fidelity predictions that closely match experimental observations.

The key findings demonstrate that the framework accurately captures stress-strain responses and fatigue life estimations, even in the presence of manufacturing-induced defects such as porosity and voids. The defect-sensitive meshing strategy proved highly effective in resolving local stress concentrations, while the Multiphysics coupling enabled the framework to simulate complex interactions among thermal, mechanical, and vibrational loads, replicating real-world aerospace and UAV operational conditions with high precision. The fatigue life prediction module exhibited strong agreement with experimental data, with prediction errors remaining below 8%, underscoring the model's robustness and practical applicability.

The contributions of this work extend beyond theoretical advancements by offering a scalable, experimentally validated tool that supports industrial certification processes, reduces reliance on expensive physical prototyping, and enhances design optimization in safety-critical industries. By capturing the combined effects of geometry, defects, material behaviour, and operational loads, the framework significantly improves the accuracy and reliability of structural integrity assessments for modern aerospace, UAV, automotive, and industrial components.

Future research directions will focus on further enhancing the predictive capabilities of the framework through integration with artificial intelligence and machine learning algorithms for real-time defect detection, adaptive mesh refinement, and automated parameter optimization. Additionally, the incorporation of real-time sensor data and digital twin technologies will enable continuous structural health monitoring, facilitating predictive maintenance and extending component service life. Expanding the framework’s capabilities to include probabilistic uncertainty quantification and real-time in-situ process monitoring during additive manufacturing presents further opportunities for advancing structural integrity assessments in next-generation manufacturing environments.

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